

# Vortex melting and decoupling transitions in $\text{YBa}_2\text{Cu}_4\text{O}_8$ single crystals

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The vortex correlation along the c-axis in high quality single crystals of  $\text{YBa}_2\text{Cu}_4\text{O}_8$  has been investigated as a function of temperature  $T$  in different magnetic fields, using the quasi-flux transformer configuration. A simultaneous sharp drop associated with the vortex lattice melting is observed in both the primary and secondary voltages ( $V_{top}$  and  $V_{bot}$ ). Just above the melting temperature, the vortices form three-dimensional line liquid with the correlation length along the c direction  $L_c \leq t$ , the sample thickness. The temperature where a resistive peak in  $R_{bot}$  develops corresponds to the decoupling temperature  $T_d$  at which the vortices lose their correlation along the c-direction and they dissolve into the two dimensional pancake vortices. The H-T phase diagram for the  $\text{YBa}_2\text{Cu}_4\text{O}_8$  single crystal is obtained.

## I. INTRODUCTION

The vortex dynamics in the mixed state of high  $T_c$  superconductors (HTSCs) remains a topic subject to intense investigation because of its importance for both the fundamental research and future applications. It is now well established that the thermal fluctuation induces a second order transition from a high temperature vortex liquid phase to a low temperature vortex glass phase for the vortex matter in a superconductor with a strong disorder. In a clean superconductor the second order transition is replaced by a first order transition from a vortex liquid to an Abrikosov vortex lattice.<sup>1</sup>

Flux melting in various high quality high  $T_c$  superconducting single crystals has been observed by different experimental techniques.<sup>2-8</sup> It demonstrates itself as a sharp resistive drop or a jump in the magnetization. An important issue concerning the melting transition is that if the vortices lose their coherence in the c direction during the melting transition or they will keep the c-axis correlations intact and then lose them at a still higher temperature.<sup>9</sup> This issue has been widely pursued by doing transport measurements with the dc flux transformer configuration. So far the results remain controversial. Doyle et al.<sup>10</sup> and Fuchs et al.<sup>11</sup> found a coincidence of the melting transition and a decoupling one on  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  (Bi2212) single crystals. However, Wan et al.<sup>12</sup> and Keener et al.<sup>13</sup> did similar measurements on Bi2212 single crystals. They concluded that the melting transition took place in a two-stage fashion, i.e., the rigid lattice at low temperature first melts into a three di-

mensional (3D) liquid followed by a decoupling transition upon an increase in the temperature. Recently Blasius et al.<sup>14</sup> performed  $\mu$ -spin rotation measurements on Bi2212 single crystals with different oxygen contents and they obtained evidence for a two stage transition of the vortex matter as a function of temperature under equilibrium conditions. On the other hand, in the  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (Y123) system a coincidence of vortex melting and loss of vortex correlation along the c-axis was observed by López et al.<sup>15</sup> A decoupling transition was not observed in the optimally doped Y123 system since the vortex in this system is always in the 3D region.

Underdoped  $\text{YBa}_2\text{Cu}_4\text{O}_8$  (Y124) is naturally stoichiometric and untwinned, it has a moderate anisotropy parameter  $\gamma$  as compared to those of Y123 and Bi2212. The weakness of the pinning strength in this material reduces the contribution from spurious effects in the melting transition in the vortex system. Thus it is a good prototype material for the investigation of the interplay between the vortex interaction and dimensionality on the vortex dynamics. Recently, we observed a first order melting transition in the Y124 single crystals.<sup>16</sup> It is of great interest to extend our previous work to examine the vortex dynamics along the c-axis. Here we report the transport data obtained in simultaneous measurements for both the primary ( $V_{top}$ ) and secondary ( $V_{bot}$ ) voltages using the dc transformer configuration, in order to investigate the vortex correlation along the c-axis in the Y124 system. It is demonstrated that in Y124 single crystals, vortex lattice (VL) melts into a 3D vortex liquid via a first order transition and that the decoupling transition is

separated from the melting one. Our results support the two stage transition scenario that the vortices first undergo a melting transition, followed by a disappearance of correlation in the transverse direction at a higher temperature.

## II. EXPERIMENTAL AND RESULTS

YBa<sub>2</sub>Cu<sub>4</sub>O<sub>8</sub> single crystals were grown by the high-pressure flux method as described previously.<sup>17</sup> These single crystals were needle-like with typical dimensions of 1.2×0.4×0.01 mm<sup>3</sup>. The zero field critical transition temperature  $T_c(0)$  of the single crystals was about 78 K. Two single crystals were used for these measurements. Each crystal was carefully cleaved to obtain optically flat surfaces with the c-axis normal to the sample surface. Gold wires were attached to the top and bottom surfaces of crystal by using Platinum epoxy. Then the crystal was heated in air at 100 °C for 1 hour, the resultant contact resistance was typically below 0.5 Ω. The electrical contact geometry for the measurement is shown in the inset of Fig. 1. The secondary voltage contact pair (5 and 6) on the bottom ab face was placed directly beneath the top face primary voltage pair (2 and 3). The distance between each voltage pair was about 0.5 mm. The resistance were measured using a low frequency (17 Hz) ac lock-in technique with an excitation current of 0.1 mA injected from contact 1 to 4 while measuring simultaneously the voltage drops  $V_{23}$  and  $V_{56}$  with the help of a Keithley 228 scanner. The magnetic field was generated by a 15 Tesla Oxford superconducting magnet and was applied parallel to the c-axis of the crystal throughout the measurements.

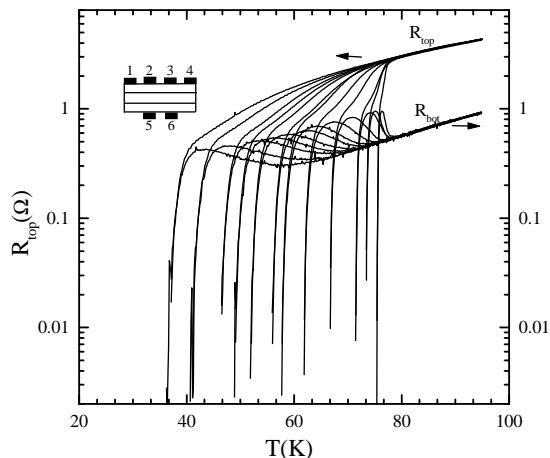


FIG. 1. The logarithmic plot of the temperature dependence of  $R_{ab}$  and  $R_c$  at different applied magnetic fields. From right to left:  $H=0.2, 0.5, 1, 2, 3.4, 6.7, 8, 10, 12$  T. Inset: the electrical contact configuration for the quasi flux transformer measurements.

Shown in Fig. 1 are the representative  $R_{top}(T)$  and

$R_{bot}(T)$  (defined as  $V_{23}/I_{14}$  and  $V_{56}/I_{14}$ , respectively) curves taken at different applied magnetic fields up to 12 Tesla for one of the Y124 single crystals. Similar results were obtained for the other crystal. The resistivity was measured by first cooling down the sample below  $T_c$  and then collecting the data while warming up the sample. While the applied magnetic fields induce a negligible depression in the superconducting onset temperature for the in plane superconductivity, they appear to considerably suppress the temperature where  $R_{bot}$  deviates from its normal state value. A sharp jump in  $R_{top}$  with a magnitude of  $R/R_n \sim 10\%$  ( $R_n$  being the normal state resistance) is clearly observed at each magnetic field. We attribute it to the occurrence of the vortex melting transition. We define the melting transition temperature  $T_m$  as the one where a sharp peak in  $dR/dT$  exists. The temperature  $T_m$  defined by  $R_{top}(T)$  and  $R_{bot}(T)$  are equal, i.e.,  $T_m^{top}=T_m^{bot}$ . This is demonstrated more clearly by plotting the derivatives of  $R_{top}$  and  $R_{bot}$  with respect to  $T$  together, as shown in Fig. 2a. Below the melting temperature,  $R_{top}=R_{bot}$ . Immediately above the melting temperature  $T_m$ ,  $R_{top}$  becomes larger than  $R_{bot}$ . As the temperature increases, both  $R_{top}$  and  $R_{bot}$  increase and the difference between  $R_{top}$  and  $R_{bot}$  becomes larger and larger. Finally near a characteristic temperature  $T_d$ ,  $R_{bot}$  reaches its maximum and at the same temperature, a small kink develops in  $R_{top}$ , as can be seen in a separated plot in Fig. 2b. It is interesting to notice that above  $T_m$ ,  $dR_{top}/dT$  decreases with the increasing temperature, reaches a minimum at  $T_d$  before a second local maximum appears at  $T_p$ . At exactly the same temperature  $T_p$ ,  $dR_{bot}/dT$  shows a local minimal. This behavior persists for the  $dR/dT$  curves at all applied magnetic fields. By plotting  $T_m$  and  $T_d$  as a function of the magnetic field, we obtain a phase diagram for this Y124 single crystal as shown in Fig. 3. Previously we have found that  $T_m(B)$  could be well described by the anisotropic Ginzburg-Landau theory and the melting line could be fitted by an empirical formula  $B_m(T)=31.4(1-T/T_c)^{1.44}$  with  $T_c=78.6$  K.<sup>16</sup> The fitting result is shown as the solid line in Fig.3. In the mean time, angular dependence of the melting transition gives for Lindermann criterion  $c_L=0.14$  and the anisotropy parameter  $\gamma=12.4$ .<sup>16</sup>

## III. DISCUSSIONS

The dc flux transformer configuration is useful means for probing the dimensionality and longitudinal correlation of vortices in the mixed state. It measures the velocity correlation for vortices running along the CuO planes of Y124 since the voltage drops  $V_{23}$  and  $V_{56}$  (and thus  $R_{top}$  and  $R_{bot}$ ) in the mixed state is induced by the motion of vortices whose velocity is determined by the integrated Lorentz force on the vortex segments of length  $l_c$  piercing the top and bottom surfaces, respectively. The relation between  $R_{top}$  and  $R_{bot}$  is determined

Fig.1 X.G. Qiu et al.

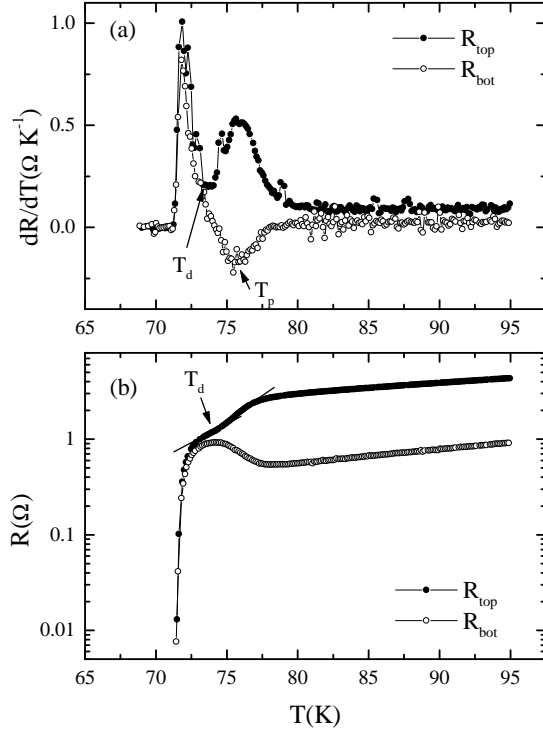


FIG. 2. (a)  $dR_{top}(T)/dT$  vs.  $T$  and  $dR_{bot}(T)/dT$  vs.  $T$  at an applied magnetic field of 1 T; (b)  $R_{top}$  and  $R_{bot}$  at 1 T. The temperature at the cross point of the two solid lines is the crossover temperature between two TAFF regions.

by the velocity of the vortices in the top and bottom surfaces. When the vortex correlation length along the  $c$ -axis is longer than the sample thickness, the voltage drops at the top and bottom surfaces would be of the same magnitude. The fact that immediately above the melting temperature  $R_{top}$  is larger than  $R_{bot}$  suggests that the  $l_c$  is smaller than the sample thickness  $t$  above the melting transition.

Above  $T_c$  in the normal state,  $R_{top}$  is larger than  $R_{bot}$  because the sample geometrical aspect, electrode arrangement and anisotropy result in a nonuniform current distribution, i.e., more current will pass through the top surface than on the bottom surface. The fact that in the normal state the ratio  $R_{top}/R_{bot}$  is nearly constant suggests that the anisotropy of Y124 is nearly temperature independent in this temperature region. Upon entering the superconducting state, the superconductivity will make an easy path for electrons to run across the CuO planes and therefore reduces the anisotropy. As we will discuss below, the vortices at this temperature region is the 2D pancakes, the voltage drop will be mainly determined by the anisotropy. Since we are measuring the resistance by passing a constant current, the decrease in anisotropy means that more current will pass through the CuO layers and that the current flowing in the bottom layers will increase. The decreasing anisotropy with decreasing temperature is reflecting in the reduction of

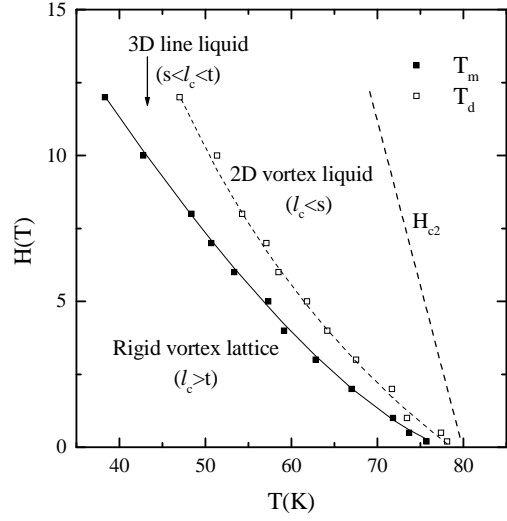


FIG. 3. H-T phase diagram extracted from the transport measurements. Solid circles are the points for the melting line, open circles are those for the decoupling line. Solid line is the fitting result with the empirical relation  $B_m(T)=31.4(1-T/78.6)^{1.44}$ . Dashed line is the decoupling line fitted with  $B_d(T)=1405.4(1-T/78.6)/T$ .  $t$  is sample thickness and  $s$  the distance between the neighboring CuO planes.

Fig.3 X.G. Qiu et al.

$dR_{bot}/dT$  as shown in Fig.2a.

In the present measurement configuration,  $R_{top}$  is equivalent to the in-plane resistance  $R_{ab}$  commonly measured in a four terminal measurement. Our previous work on the in-plane resistivity demonstrated that for  $R_{top}(T)$ , above the melting temperature in the liquid state, there are two distinct parts where  $\ln R_{top}$  shows linear dependence upon  $1/T$  with different slopes, which is a typical characteristic for thermally activated flux flow (TAFF) behavior.<sup>16</sup> We have identified the temperature  $T_d$  where the crossover between the two TAFF regions occurs as the decoupling transition through an activation energy analysis. The decoupling temperature is described by<sup>9</sup>

$$B_{cr} = \frac{\Phi_0^3}{16\pi^3 k_B T s e \lambda_{ab}^2 \gamma^2}, \quad (1)$$

where  $s$  is the interlayer spacing between the neighboring CuO planes. With a  $\gamma$  value of 12.4 a satisfied fit is obtained by Eq. (1) for the decoupling line shown as the dashed line in Fig. 3.

We notice that the temperature where  $R_{bot}$  shows a maximum corresponds to exactly the same temperature where a crossover between two different TAFF regions occurs as we have identified before. Such a peak resembles that of the out-of-plane resistance  $R_c$  often appears in single crystals with large anisotropy such as Bi2212.<sup>18,19</sup> However it can be seldom seen in single crystal with moderate anisotropy such as fully oxidized Y123. Although there is no consensus on the occurrence of the peak in  $R_{bot}$  and  $R_c$  yet, one possible reason for it could be the tunneling of vortices over the  $c$ -axis barrier in the liquid

state following by the complete coupling of CuO planes. Recently, there have been considerable efforts devoted to the study of interlayer charge dynamics by far infrared reflectivity.<sup>20,21</sup> Studies on the interlayer charge dynamics with the electric field component  $\mathbf{E}$  polarized along the c-axis reveals that above a characteristic temperature  $T_{pl}$ , the superconductor behaves like a poor metal or an ionic insulator. The carriers are confined inside the CuO planes and the c-axis resistivity is controlled by the interlayer tunneling. The c-axis coherence is signaled by the appearance of a reflectivity edge associated with the Josephson plasma from the intrinsic Josephson junctions.<sup>22,23</sup> Above  $T_{pl}$ , the electron transport along the c-axis is incoherent. Below  $T_{pl}$ , coherence is built up for the interlayer carrier transport. Therefore, given the high transition temperature and weak interlayer magnetic coupling between the pancake vortices in the neighboring CuO planes,  $T_d$  would quite possibly correspond to  $T_{pl}$  (the Josephson plasma frequency) at which the phase coherence and thus the superconductivity is built up for the entire system along the c-axis. The suppression of the onset temperature for c-axis superconductivity by an applied magnetic field is due to the breakdown of the phase coherence along the c-axis by a magnetic field. This is consistent with the model proposed by Briceño et al.<sup>19</sup> and later developed by Suzuki et al.<sup>24</sup> who suggested that phase fluctuation induced dissipation controlled the dissipation and could be well described by the Ambegaokar-Baratoff theory.

Although the picture of vortex melting has been widely accepted, the mechanism of the vortex melting has yet not well understood. Recently, Nonomura et al.<sup>25</sup> carried out Monte Carlo simulations of the three dimensional frustrated XY model, in which the melting temperature was determined by the helicity modulus along the c-axis. They found that the melting transition is propagated through vortex entanglement. At the melting temperature, the percentage of entangled vortices abruptly changes. Upon increasing the temperature, the entanglement length becomes smaller than the sample thickness and decreases rapidly. The dissipation is governed by the cutting of vortices above the melting temperature. As a consequence of the entanglement mechanism of the FLL melting,  $T_m$  is scaled by the inverse of the system size along the c axis. Our results can be explained by their simulation results very well since we indeed observed a melting transition into 3D line liquid with its correlation length  $l_c$  smaller than the sample thickness  $t$ .

The vortex melting scenario has been questioned by Moore<sup>26</sup> who argued that the melting transition could just be a second order crossover of the vortex matter from a three dimensional behavior to a two dimensional one when the  $l_c$  in the vortex liquid becomes compatible to the sample thickness  $t$ . Because  $l_c$  grows very rapidly as the temperature is lowered, the crossover region appears narrow enough to be misinterpreted as a first order melting transition. For a cutting length of the sample thickness  $t$ , the cutting temperature can be calculated

according to<sup>27</sup>

$$B_{cut} = \frac{\Phi_0 \varepsilon_0}{\gamma^2 L k_B T}, \quad (2)$$

by substituting  $L$  with  $t \approx 0.01$  mm. Here  $\phi_0 = 2.07 \times 10^{-7}$  Gauss cm<sup>-2</sup> is the flux quantum,  $\varepsilon_0 = \Phi_0^2 \ln \kappa / 16 \pi^2 \lambda_{ab}^2(T)$ ,  $\kappa$  being the Ginzburg-Landau parameter and  $\lambda_{ab}(0) \approx 2000 \text{ \AA}$ , the penetration depth in the ab plane. The obtained vortex cutting line lies slightly below the melting line  $B_m(T)$ . Although our result can also be qualitatively explained with this argument, it is not clear why such a sharp crossover is not observed in thin films (strong pinning disorder) since in any sample with a finite thickness larger than the distance between neighboring CuO planes, a crossover temperature is expected. One reason could be that the relatively smaller numbers of pinning centers in the single crystals (weak pinning) than in the thin films result in a larger Larkin correlation length  $L_p$  inside which an ordered VL can persist.<sup>28</sup> In the case of thin films, the transverse correlation length is smaller than the average lattice spacing, only a second order glass transition can be observed.<sup>29</sup> This in turn suggests that a regular VL with a relatively large radius is a necessity for the occurrence of a melting transition. This is consistent with the fact that artificially introduced pinning centers will induce a small Larkin length and smear out the melting transition. Further work on the study of the relationship between pinning strength and Larkin length need to be done in order to clarify this point.

Our results suggest the following physical scenario: in a clean Y124 single crystal, below the melting temperature  $T_m$ , the vortices form a rigid VL with  $l_c \gg t$ . As the superconductor is warmed up, at  $T_m$ , VL melting occurs. At this stage, the vortices lose their translational coherence while keeping the correlations along the c-axis. Thus the vortices in the temperature region just above the melting transition are in a 3D line liquid state. At this temperature region, the vortex form a kind of entangled vortices with their entanglement length  $l_c$  smaller than the sample thickness  $t$  but much larger than the distance  $s$  between the CuO planes. The dissipation is governed by the vortex cutting and recombination. As the temperature increases, the correlation length in the c-axis becomes smaller and smaller and the difference between  $R_{top}$  and  $R_{bot}$  gets larger and larger. Finally at the temperature  $T_d$ , inter-plane decoupling occurs ( $l_c < s$ ) and the vortices lose the coherence in the c direction and the vortices dissolve into 2D pancake vortices that move independently in the individual CuO planes.

#### IV. CONCLUSIONS

In conclusion, we have observed the melting transition in Y124 single crystals. The vortices following the melting transition are in the 3D line liquid state with a

correlation length in the  $c$ -direction  $l_c$  smaller than the sample thickness but larger than the distance between the CuO planes of Y124. The temperature at which a resistive peak exists at  $R_{bot}$  is found to correspond to the interlayer decoupling transition temperature. Above the decoupling temperature, the vortices lose their coherence in the  $c$ -direction and the dissipation would be governed by tunneling of 2D vortices across the CuO planes. Our results also suggest that the interlayer decoupling transition is a continuous crossover rather than a sharp transition.

## V. ACKNOWLEDGMENTS

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